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Alhaddad, S.M.S.; Helmons, R.L.J.

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EXPERIMENTAL INVESTIGATION OF SEDIMENT EROSION GENERATED BY A COANDĂ-EFFECT-BASED POLYMETALLIC-NODULE COLLECTOR

S. Alhaddad[1] and R. Helmons[2]

Abstract: Owing to the absence of direct contact between hydraulic polymetallic-nodule collectors and seabed, hydraulic collection is deemed, from an environmental point of view, the most preferred technique in nodule mining. To design a hydraulic collector that results in minimum sediment disturbance, it is crucial to develop a solid understanding of the interaction between the collector and the sea bed. To this end, we performed a series of small-scale experiments where several operational conditions were tested, yielding the first quantitative data for sediment erosion resulting from the movement of a hydraulic collector over a sand bed. This paper presents and discusses the experimental results and observations. It is found that the collector's forward velocity is inversely proportional to the bed-sediment erosion depth, since the bed is exposed to the flow for a longer time when the collector drives slower and vice versa. Contrarily, an increased jet velocity leads to a larger erosion depth. Furthermore, when the collector underside is nearer to the bed, a larger sediment layer is exposed to the water flow, resulting in a larger erosion depth. Finally, the experimental results show that a larger amount of water entrained into the collection duct results in a smaller erosion depth, implying that the flow velocities under the collector are lower in this case.

Key words: deep sea mining, sediment erosion, polymetallic nodules, hydraulic collector, Coandă effect

[1] Delft University of Technology, the Netherlands, S.M.S.Alhaddad@tudelft.nl

[2] Delft University of Technology, the Netherlands and Norwegian University of Science and Technology, Norway R.L.J.Helmons@tudelft.nl

1 INTRODUCTION

Aiming for a carbon-free future, societies are steadily moving toward battery-powered vehicles and utilizing renewables. Consequently, there is an increased demand for critical materials, such as lithium and cobalt. Recently, companies have turned their attention to the deep-sea floor, since it contains immense untapped collections of key materials and rare-earth elements. Large quantities of these are embedded into potato-sized lumps termed polymetallic nodules (Schulz et al., 2018). These are rich in cobalt, copper, manganese, nickel and other precious materials. Polymetallic nodules are found in abundance on the seabed within the Clarion Clipperton Zone (CCZ) (Hein et al., 2020) at typical water depths of 4-6 km.

Companies are gearing up to mine the deep-sea, but environmental impact of mining is still a major concern (Boetius and Haeckel, 2018). Given that nodules are usually partly or completely buried into the seabed sediment (see Figure 1), some sediments are inevitably picked-up while harvesting nodules. This means that collectors, during mining operations, create a sediment plume as they travel across the ocean floor (Elerian et al., 2021). This plume could possibly drift for long distances and disrupt ecosystems. Therefore, it is imperative to fully understand the interaction of hydraulic collectors with the sea bed, so as to pave the way for more environmentally-friendly equipment design in the future.

Figure 1. Undisturbed nodule-sediment sample demonstrating the burial of polymetallic nodules (Museum National d'Histoire Naturelle Box Corer)

There is dearth of direct measurements detailing flow fields and quantifying sediment erosion generated by deep-sea mining equipment. This paper presents and discusses experimental results of small-scale tests carried out in a water flume, where a hydraulic collector operating based on Coandă-effect moves over a submerged sand bed. We conducted a series of experiments in which several operational conditions were tested, providing the first quantitative data for sediment erosion associated with mining by a hydraulic collector. The experimental measurements provide new insights into the effect of crucial parameter for the effectiveness of the collector on the degree of bed-sediment disturbance. The measurements acquired within this study may also be used for the validation of numerical models utilized for the improvement of the collector design.

2 COLLECTOR PRINCIPLE

The collector considered in our study utilizes Coandă-effect to dislodge and collect nodules hydraulically, while it drives over them. Intriguingly, Coandă effect, named after the Romanian scientist Henri Coandă, is the tendency of a jet flow to keep adhering to an adjacent surface, even if it curves (Reba, 1966). Figure 2 shows a diagrammatic representation of the fundamental design of our Coandă-effect-based collector. It consists of four concentric surfaces, forming three ducts: main jet duct, secondary jet duct and a collection duct. As a result of the Coandă effect, the high-velocity water jets flowing through the jet ducts follow the curvature of the upper plate. This causes an entrainment of the ambient water towards the collection duct, which produces a pressure difference (suction) under the collector, thereby dislodging nodules from the seabed and carrying them towards the collection duct (Alhaddad et al., 2022).

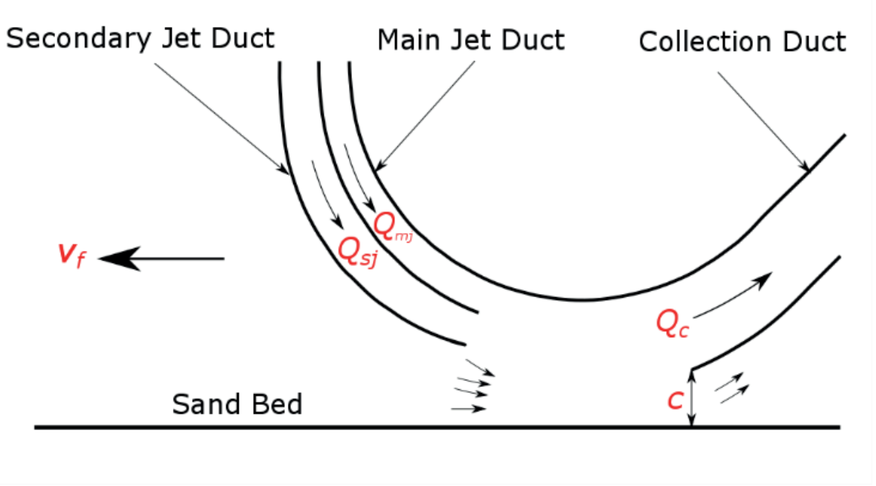

Figure 2. Diagrammatic representation of the collector head; v_f is the forward velocity of the collector, c is bottom clearance, Q_{mj}, Q_{sj} and Q_c are the flow rate through the main jet duct, the secondary jet duct and the collection duct, respectively

3 EXPERIMENTS

The present study aims at quantifying bed-sediment erosion resulting from mining nodules by a hydraulic collector as well as investigating the effect of the parameters primarily controlling the pick-up efficiency of the considered collector on sediment erosion. These parameters are main jet velocity, secondary jet velocity, collector's forward velocity and bottom clearance. This section describes the experimental setup, instrumentation, test procedure and characterization of sand deposit, respectively.

3.1 Experimental setup

The experimental setup is composed of several components: the collector head, a mobile carriage, three PVC hoses, water pumps, and a water flume. The collector head (20 cm wide) was fastened on a mobile carriage that can automatically drive over railways at the target forward velocity. Each jet duct was connected to a water pump using a hose of 40 mm inner diameter, whereas the collection duct was connected to a third water pump using a hose of 63 mm inner diameter. The flow rate through the three ducts is controlled using frequency drives. The water flume, where the tests with the collector head are conducted, is 15 m long, 0.4 m wide and 0.47 m high. The water flume was divided into two compartments using a gate made of a geotextile filter (opening size = 0.04 mm), which allows water to pass through it while it holds sediments in place. The tests are performed in one compartment ('testing compartment') while the other compartment ('sedimentation compartment') is used to collect the sand-water mixture flowing through the collection duct. At the end of each experiment, the sediment particles settle into the sedimentation compartment, so the sediment can be reused in next experimental runs. Figure 3 shows a real view of the experimental setup.

Figure 3. Side view of the experimental setup

3.2 Instrumentation

The experimental setup was equipped with two electromagnetic flowmeters to monitor the flow rate in the jet hoses and an acoustic flowmeter to monitor the flow rate in the collection hose. To measure bed disturbance depth, three optical sensors (optoNCDT 1302) were attached to the mobile carriage, which can measure the distance from the sensor to the sand bed, while the carriage drives over the water flume. As the optical sensors were used underwater, they were mounted into a custom-built waterproof housing. Besides, a wheel encoder was used to pinpoint the position of sensors along the flume.

3.3 Test procedure & data acquisition

Every experiment was conducted following the next sequence of steps:

- The water flume is half filled with clean water.
- Sand is placed into the testing compartment until reaching the target depth, which is defined based on the target bottom clearance.
- The sand bed is levelled using a level wooden plate, which was fastened on the mobile carriage. To level the bed, the carriage drives several times back and forth along the flume.
- Additional clean water is supplied into the water flume until reaching a water level of 40 cm. The flume is not fully filled with water to avoid that it will overspill due to the surface waves generated by the movement of the collector head.
- The carriage slowly drives forward over the flume to measure the initial bathymetry using the optical sensors. Then, it drives backward towards the starting point.
- The water pumps are switched on at the frequencies required to obtain the target flow rate in each duct (calibration was done earlier). To make sure there is no water spill, two submersible pumps are used to drain water constantly from the flume.
- The mobile carriage drives forward at the required forward velocity and halts and the end of the railways; a sensor was mounted at each end point of the railway to force the carriage to halt there.
- After waiting about 2 minutes, to allow suspended sediment particles to settle down, the carriage drives over the flume to measure the final bathymetry.

Table 3.2 summarises the initial conditions of the experiments conducted within this study. The bed disturbance depth for each test was quantified based on the difference between the initial and final bathymetries.

Table 1. A summary of the experiments conducted within this study

Test #	Q_{mj} **[l/s]**	Q_{sj} **[l/s]**	Q_c **[l/s]**	c $[mm]$	v_f **[cm/s]**
1	5	6.25	12.70	7.5	25
2	5	6.25	12.70	7.5	12.5
3	3	4.70	9.70	7.5	25
4	4	4.70	10.70	7.5	25
5	5	4.70	11.70	7.5	25
6	4	0.00	6.00	7.5	25
7	4	3.13	9.13	7.5	25
8	4	4.70	8.70	7.5	25
9	4	4.70	9.70	7.5	25
10	4	4.70	10.70	13.5	25

3.4 Characterization of sand deposit

A fine sand (GEBA weiss) of $d_{50} = 0.140$ mm was used in the experiments. The Laser Diffraction technique was used to determine the cumulative grain size distribution (see Figure 4). It is to be noted that the seabed sediment, in which the polymetallic nodules are buried, is primarily composed of clay. Nonetheless, we conducted our experiments using sand instead, to conduct a larger number of tests and to investigate more operational conditions; using clayey sediment requires more time and effort and will be considered in future research.

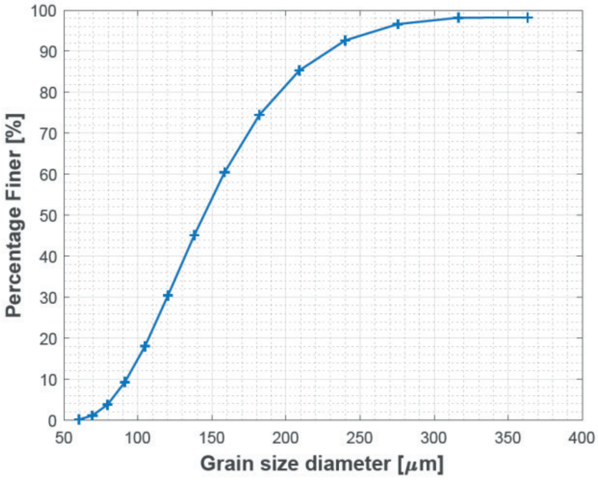

Figure 4. Cumulative grain size distribution of the sand used in the experiments

4 EXPERIMENTAL RESULTS

4.1 General description of sediment erosion

While the collector drives forward, a layer of sand is eroded and part of which is picked-up by the collector towards the collection duct. The rest of the eroded sand is suspended in the water column behind the collector, consequently generating a turbidity flow (see Figure 5). The reason why not all eroded sand ends up into the collection duct is that not only do the jets entrain water to the collection duct, but also entrain/inject water behind it (see Figure 2). This water flows backward, in the opposite direction of the carriage movement, with sufficient velocity to pick-up sand particles in suspension. The suspended particles settle down at the sand bed within 1-2 minutes after the end of an experimental run.

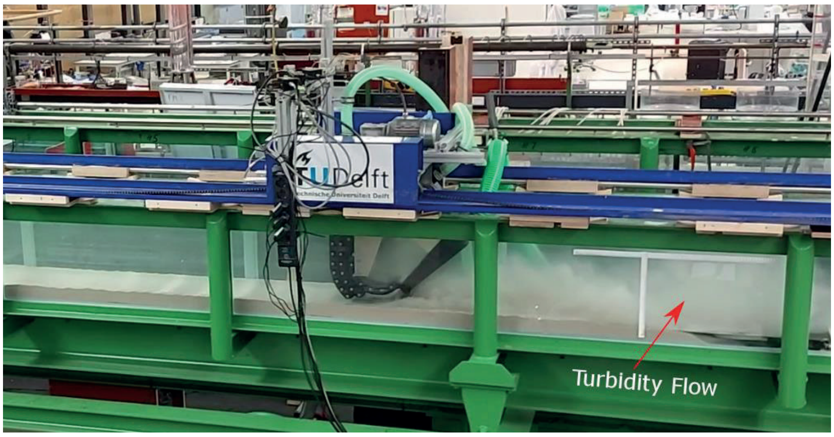

Figure 5. The experiment in progress

Owing to sand erosion, a shallow trench is created at the sand bed. Our visual observations, along with the measurements, show that sand erosion is not uniform across the flume width. Rather, the erosion is the highest at the middle of the flume width (which coincides with the middle of the collector width) and declines towards the position of the collector sides. This is in agreement with the lateral structure of the jets velocity.

In the following, we will analyse the relationship between the amount of sand erosion and important parameters for the effectivity of the present collector. The erosion depths documented in this section are measured at the middle of the flume width, while the deposition depths are the average of the depths of the sand layer deposited near the side walls of the flume, where sand erosion does not occur. Two erosion depths are distinguished in this paper: net erosion depth, which results from the sand collected by the collector, and total erosion depth, which results from the sand collected by the collector and the sand picked up in suspension behind the collector. In other words, the total erosion depth is the summation of the net erosion depth and the deposition depth.

4.2 Main & secondary jets

The erosion and deposition depths were measured for experimental runs of different flow rates through the main jet Q_{mj} (see Figure 6 left). It can clearly be seen that a higher Q_{mj} results in a larger erosion depth. This makes sense, as a higher Q_{mj} leads to higher flow velocities above the sand bed and, by extension, a higher flow-induced shear stress, thereby picking-up more sand particles. The same holds for the effect of the flow rates through the secondary jet Q_{sj}(see Figure 6 right). However, it is observed that the erosion depth is minimal, when Q_{sj} is zero, indicating that the presence of a secondary jet enhances sand erosion.

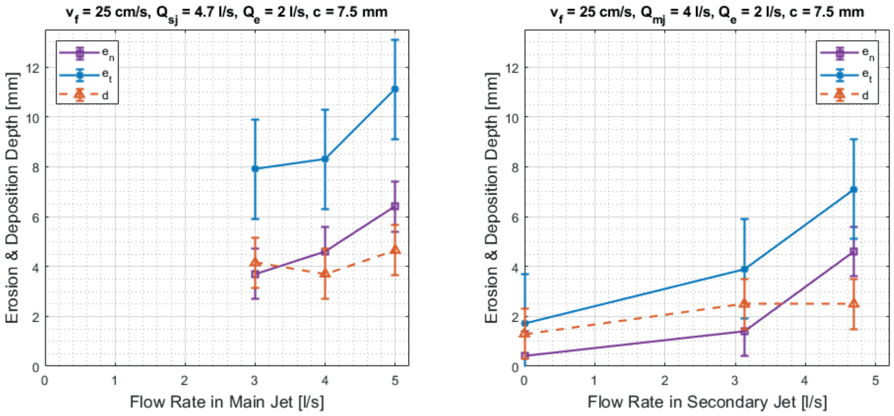

Figure 6. Effect of the flow rate in the main jet (**left**) and the flow rate in the secondary jet (**right**) on the erosion depth; e_n is net erosion depth, e_t is total erosion depth at the middle of flume width, d is the deposition depth

4.3 Collector's forward velocity

The collector's forward velocity v_f plays an influential role in the erosion process. The experimental results distinctly demonstrate that a lower v_f leads to a larger erosion depth (see Figure 7). This correlation is expected, as a lower v_f means that the sand bed is exposed to the water jets for a longer time, consequently eroding more sand particles.

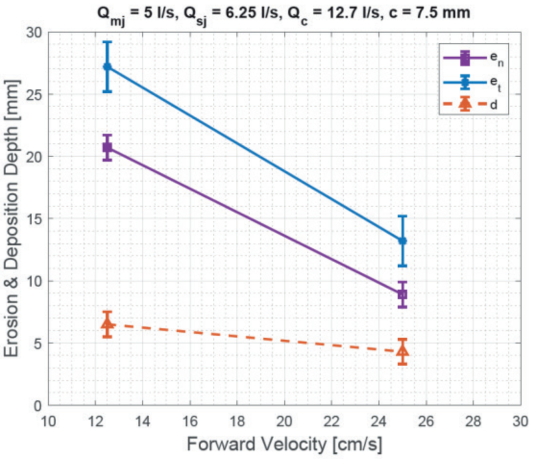

Figure 7. Effect of collector's forward velocity on the erosion depth

4.4 Bottom clearance

The experimental results show that a smaller bottom clearance results in a larger erosion depth (see Figure 8). This correlation is attributed to the fact that a larger sand layer is exposed to the water jets, when the underside of the collector is closer to the sand bed.

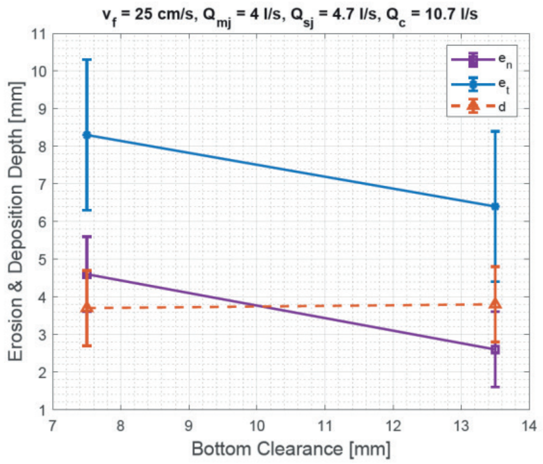

Figure 8. Effect of bottom clearance on the erosion depth

4.5 Water entrained into the collection duct

In addition to the previous parameters investigated, we also explored the effect of the flow rate of water entrained into the collection duct Q_e on the erosion depth (see Figure 9). It can be inferred from the experimental results that a larger Q_e leads to a smaller erosion depth. This indicates that the flow velocities near the sand bed are larger in the case of a smaller Q_e.

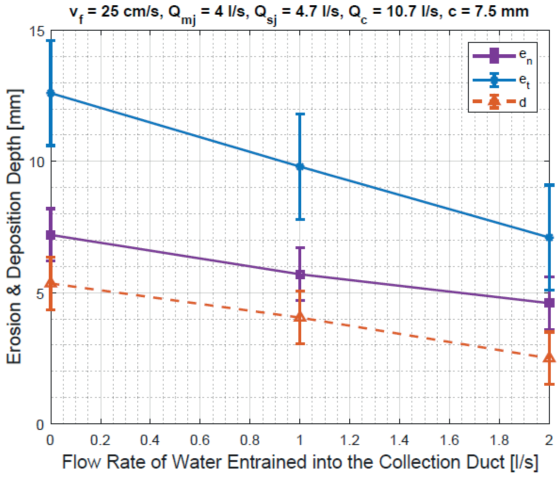

Figure 9. Effect of the flow rate of water entrained into the collection duct on the erosion depth

5 CONCLUSION

To pave the way for a more environmentally-friendly design of a Coandă-Effect-Based hydraulic collector, we carried out a set of small-scale experiments to explore bed-sediment erosion. Several operational conditions were tested, demonstrating the effect of a handful of critical parameters on the bed-sediment erosion. The experimental results highlight the importance of optimizing the collector's forward velocity, since it is inversely related to bed erosion depth. In contrast, an increased jet velocity leads to a larger erosion depth. Furthermore, a smaller erosion depth is observed when the bottom clearance is larger. It is revealed that a larger amount of water entrained into the collection duct results in a smaller erosion depth.

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